NASA/TM—2010-216355

Path Length Fluctuations Derived From Site Testing Interferometer Data

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July 2010

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Level of Review: This material has been technically reviewed by technical management.

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Abstract

To evaluate possible sites for NASA's proposed Ka-band antenna array, the NASA Glenn Research Center has constructed atmospheric phase monitors (APM) which directly measure the tropospheric phase stability. These instruments observe an unmodulated 20.2 GHz beacon signal broadcast from a geostationary satellite (Anik F2) and measure the phase difference between the signals received by the two antennas. Two APM's have been deployed, one at the NASA Deep Space Network (DSN) Tracking Complex in Goldstone, California, and the other at the NASA White Sands Complex, in Las Cruces, New Mexico. Two station-years of atmospheric phase fluctuation data have been collected at Goldstone since operations commenced in May 2007 and 0.5 station-years of data have been collected at White Sands since operations began February 2009. With identical instruments operating simultaneously, we can directly compare the phase stability at the two sites. Phase stability is analyzed statistically in terms of the root-mean-square (*rms*) of the tropospheric path length fluctuations over 10 min blocks. Correlation between surface wind speed and relative humidity with interferometer phase are discussed. For 2 years, the path length fluctuations at the DSN site in Goldstone, California, have been better than 757 μm (with reference to a 300 m baseline and to Zenith) for 90 percent of the time. For the 6 months of data collected at White Sands, New Mexico, the path length fluctuations have been better than 830 μm (with reference to a 300 m baseline and to Zenith) for 90 percent of the time. This type of data analysis, as well as many other site quality characteristics (e.g., rain attenuation, infrastructure, etc.), will be used to determine the suitability of both sites for NASA's future communication services at Ka-band using an array of antennas.

1.0 Introduction

As NASA progresses into the 21st century, NASA's communications network systems (e.g., deep space and near earth) are expected to transition into the use of the Ka-band spectrum. These network systems operating at Ka-band, will be required to provide services with a system availability higher than 99 percent (currently at ~ 90 percent) and gigabyte data rates (currently ~ Megabyte rates) for human exploration. If all proceeds as planned, the aging monolithic 70-m antennas of the Deep Space Network (DSN) are expected to be replaced (~ 2020) with a ground-based array of smaller aperture antennas (e.g., 34 m or possibly 12 m). The new system will provide the flexibility and reliability necessary for the demands of NASA's upcoming mission roster, reduce single-point failures, and allow electronic steering and multi-beam operational capabilities. However, the atmospheric phase stability of a particular site must be known before implementation of a ground-based array can proceed. The statistical knowledge of the atmospheric fluctuations will lead to mitigation techniques to further improve system margin and reduce cost.

Atmospheric phase instability (decorrelation of a propagating plane wave phase front) arises because earth's upper atmosphere (troposphere) contains large amounts of inhomogeneous distributions of water vapor exposed to turbulent air flow conditions. This property induces variations in the precipitable water vapor content that changes the refractivity of the medium, which directly leads to variations in the effective electrical path length of an electromagnetic wave propagating through this layer of the atmosphere (See Fig. 1). Such variations are seen as "randomly modulated phase noise" by radio arrays and will inherently degrade the performance of widely distributed ground-based antenna systems. A two-element interferometer is the optimal system to directly measure atmospheric phase stability at any given site (Ref. 1).

NASA Glenn Research Center, in collaboration with the Jet Propulsion Laboratory and Goddard Space Flight Center, has constructed and deployed two APM's (two-element interferometer). The first APM was deployed at Goldstone, California, and we have collected over 2 years of phase fluctuation measurements (operation started May 2007). The second APM was deployed at White Sands, New Mexico, where we have collected over 6 months of data (operation started February 2009). The results of this data analysis will directly determine the necessary system design parameters and identify possible mitigation techniques to optimally operate a Ka-band array system at both locations.

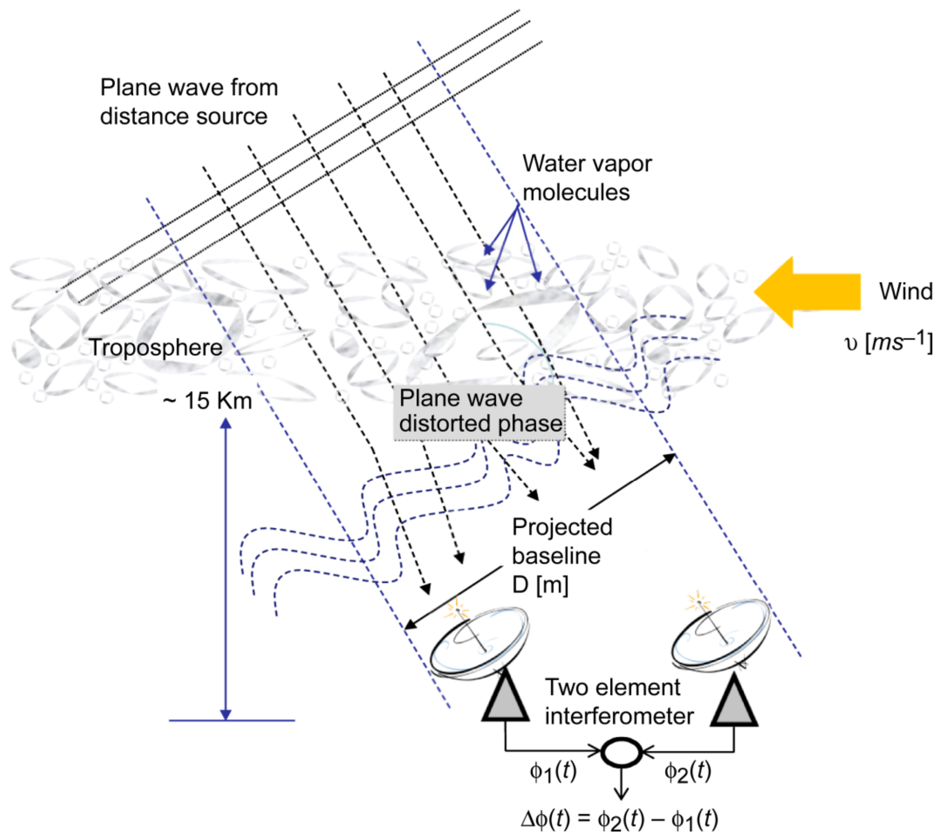

Figure 1.—Statement of the problem: Model of atmospheric phase fluctuations. Water vapor is contained in screens (a defined volume of water vapor molecules) of various sizes, which are transported across the antennas. The motion of the screens causes phase fluctuations in radio waves passing through them.

2.0 Field Deployment and Measured Performance

Two APM's have been constructed (Ref. 2). The first interferometer was deployed in May 2007 at 3408 ft altitude on an east-west baseline of 252 m at the Goldstone DSN Complex, near Barstow, California. A similar interferometer was installed at 4821 ft on a north-south baseline of 208 m at The White Sands Tracking and Data Relay Satellite (TDRS) Complex, near Las Cruces, New Mexico. Both interferometers receive the Anik F2 20.2 GHz beacon signal**.** A signal-to-noise ratio (SNR) of approximately 80 dB·Hz was measured at both locations at the beginning of operation. Before deployment, the instrument performance was evaluated in the laboratory environment (no atmospheric contributions) and constantly showed a root-mean-square (rms) of 1.5° over 600-s integration intervals.

A sample time series of measured interferometer phase fluctuations observed from February 5 to 9, 2009 by the White Sands Interferometer is depicted in Figure 2. These time series illustrate a typical instrument's operational performance.

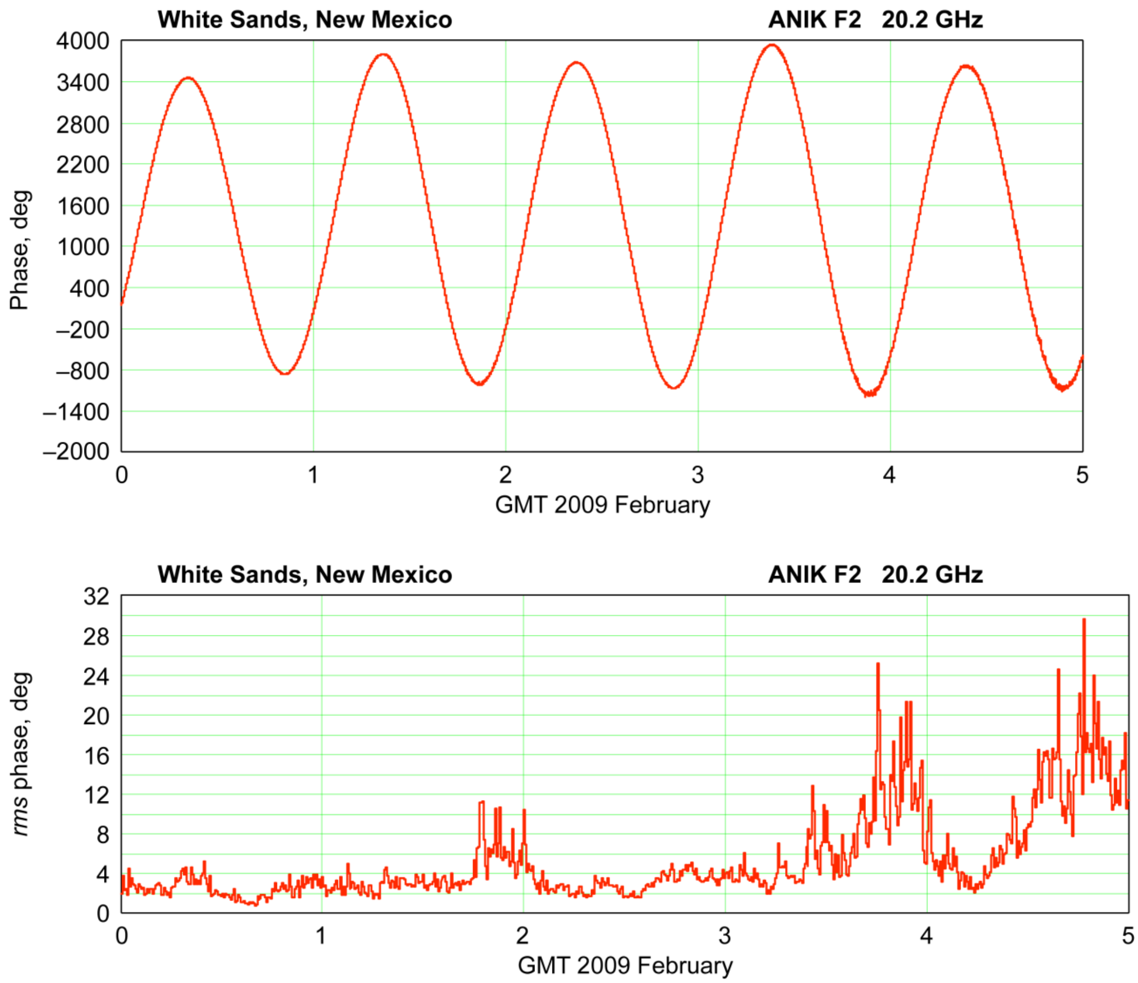

Figure 2.—Sample time series of interferometer phase measurements at White Sands, New Mexico. These data are typical of good and bad conditions at this site. Upper; Five days of 1-s measurement data (includes satellite motion). Lower; Phase fluctutation; *rms* of 1-s measurements over 600-s intervals for 5 days.

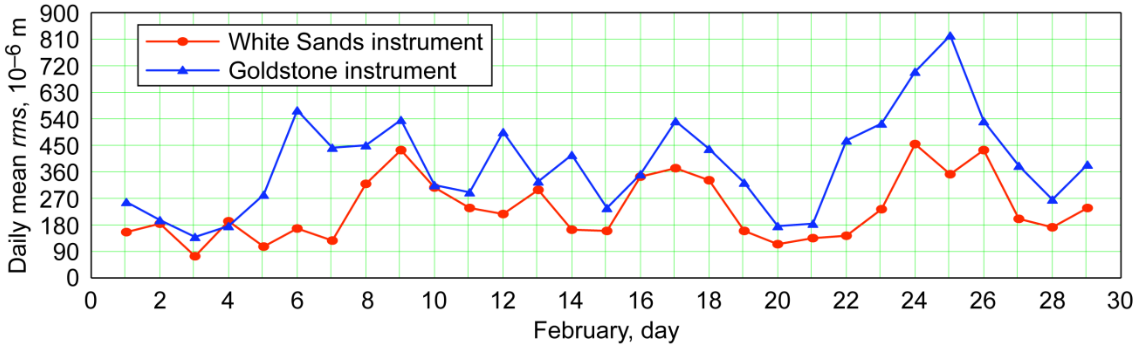

Figure 3.—Simultaneous site testing results. The *rms* phase fluctuations are reference to zenith and to a 300 m baseline.

In the upper portion of Figure 2, we can see the large phase swings (variations) that are due mainly to satellite motion. The lower portion of Figure 2 depicts the corresponding time series of the *rms* of the phase fluctuations computed in 600-s intervals after calibration of the phase data has been performed (see Section 3.0). Notice that most of the energy (proportional to the *rms*) are above the system phase noise of 1.5° *rms*, indicating the presence of atmospheric fluctuations on scales much shorter than 600-s. What is also evident is the presence of a diurnal variation of the phase fluctuations (*rms*). This is an expected result since the atmosphere is quieter at night than it is during the day.

With identical instruments operating simultaneously, we can directly compare the phase stability at Goldstone and White Sands. With only 6 months of data collected simultaneously, it is too premature to draw firm conclusions about the site differences, which will require measurements extending over several seasons and even several years. The White Sands and Goldstone interferometers both receive the 20.2 GHz satellite signal (ANIK F2) at two different elevation angles (51.8° and 48.5° respectively) and at two different interferometer baselines (208 and 252 m, respectively) and it is necessary to extrapolate the measured *rms* results to an observation angle of zenith (90°) and to a common baseline of 300 m (Ref. 1). A preliminary look at the data results for the month of February 2009, from simultaneous site testing, is presented in Figure 3. This preliminary assessment of the data indicates that the daily mean *rms* of the path length fluctuations (directly proportional to the site phase stability) at White Sands is slightly better than at Goldstone for this particular month.

3.0 Data Processing

Before the data can be statistically analyzed, the phase fluctuations induced by the atmosphere must be isolated from those introduced by the system (i.e., motion of the satellite, slow varying system drift, and random system thermal noise). The foundation for (and validation of) this calibration procedure can be found in (Ref. 3), and a summary of the steps is provided below.

First, the recorded data (1-s) is unwrapped (the interferometer records relative phase within a ± 180° range), so that a continuous differential phase curve is established (see Fig. 2, upper). The 24-hr data is then divided into 144 blocks of 600 s (10 min) intervals. Blocks containing bad data (e.g., data recorded during maintenance visits, system-induced phase jumps, etc.) are removed. Within each good 10 min block, a 2nd order polynomial is fit to the data using a least mean square approach and subtracted. The final result of this process is the phase fluctuations due solely to the atmosphere and system noise over 10 min intervals in a given 24-hr period. Figure 4 shows the corresponding 1-s phase fluctuations after the satellite motion was removed for the data collected from the February 5 to 9, 2009 (compare with Fig. 2, upper).

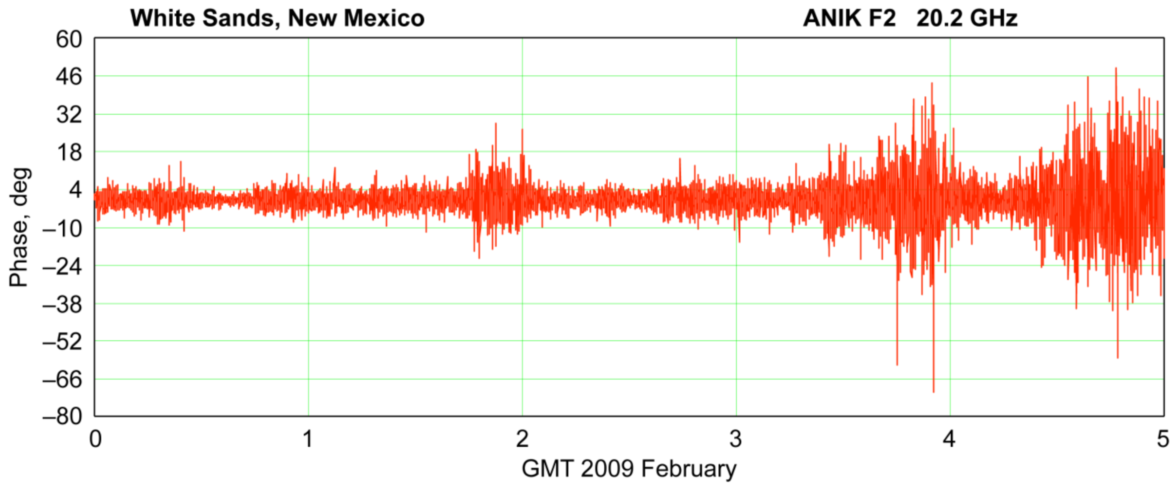

Figure 4.—Interferometer phase (1-s) over five consecutive days in February 2009 (satellite motion was removed).

4.0 Statistical Results

The overall cumulative distributions derived from all the measured phase fluctuations (*rms*) at the two sites are presented in Figure 5. The Goldstone cumulative distribution functions (CDF) include 22 months of data while the White Sands distribution only includes 6 months of data. The CDF is derived from a histogram of observations that included the *rms* (obtained by averaging the 1-s measured phase over 600-s).

The distributions are summaries for line-of-sight first-order statistics. The 90th percentile for Goldstone is about 22° and for White Sands is about 19° (6 months).

If the 90 percent *rms* phase fluctuations at line-of-sight are converted to path length and referenced to zenith we obtain 615 µm for White Sands and 680 µm for Goldstone. These results seem to be consistent from the results obtained during simultaneous site testing discussed in Section II. However, when the fluctuations are extrapolated to a common baseline (i.e., 300 m), we observe that in actuality, the Goldstone site (757 µm) slightly outperforms the White Sands site (830 µm). This result is a more direct comparison of the characteristics of the two locations.

In order to make an assessment of the seasonal variations (summer versus winter, etc.) we derived the monthly median phase *rms* for both sites. The derived statistics are presented in Figure 6. The results of the seasonal variation at Goldstone are as expected. The summer months (June to September) tend to promote higher phase fluctuation *rms* than winter months (November to February). In the summer months the atmosphere is more turbulent (high heat, more storms, abundance of clouds, high humidity) than in the calm winter months (low heat, little cloud coverage, lower humidity). These are expected results that have been seen by other site test interferometers at sites around the world (Refs. 1 and 4).

The site comparisons done by using the seasonal variations statistics above cannot be fully analyzed at this point since the White Sands site does not have enough data for evaluating all the seasonal variations.

In order to statistically evaluate the hour-to-hour variations (diurnal) at each site we derived the hourly 25th, 50th, 75th and 90th percentiles from the measured phase fluctuation (*rms*) at both sites. The statistical results are presented in Figure 7. From these results we can see a clear variation between night and day. This general result is consistent with other interferometer measurements taken at the Very Large Array (VLA) (Ref. 4) and indicates similar atmospheric patterns. The results so far indicate that the afternoons in Goldstone are slightly better than those of White Sands. During the night the performance at both sites was about the same.

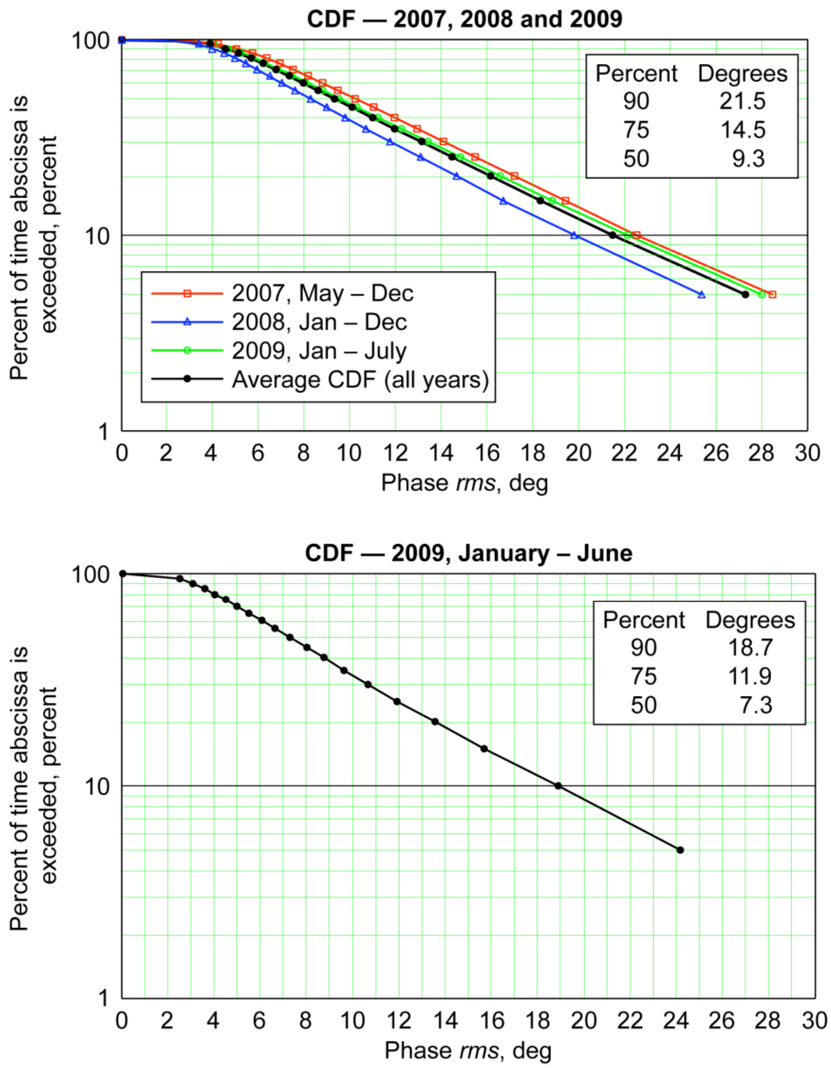

Figure 5.—Upper; Yearly and the mean cumulative distribution function of the phase fluctuations over 600-s intervals for Goldstone, California. Lower; Yearly and the mean cumulative distribution function of the phase fluctuations over 600-s intervals for White Sands, New Mexico.

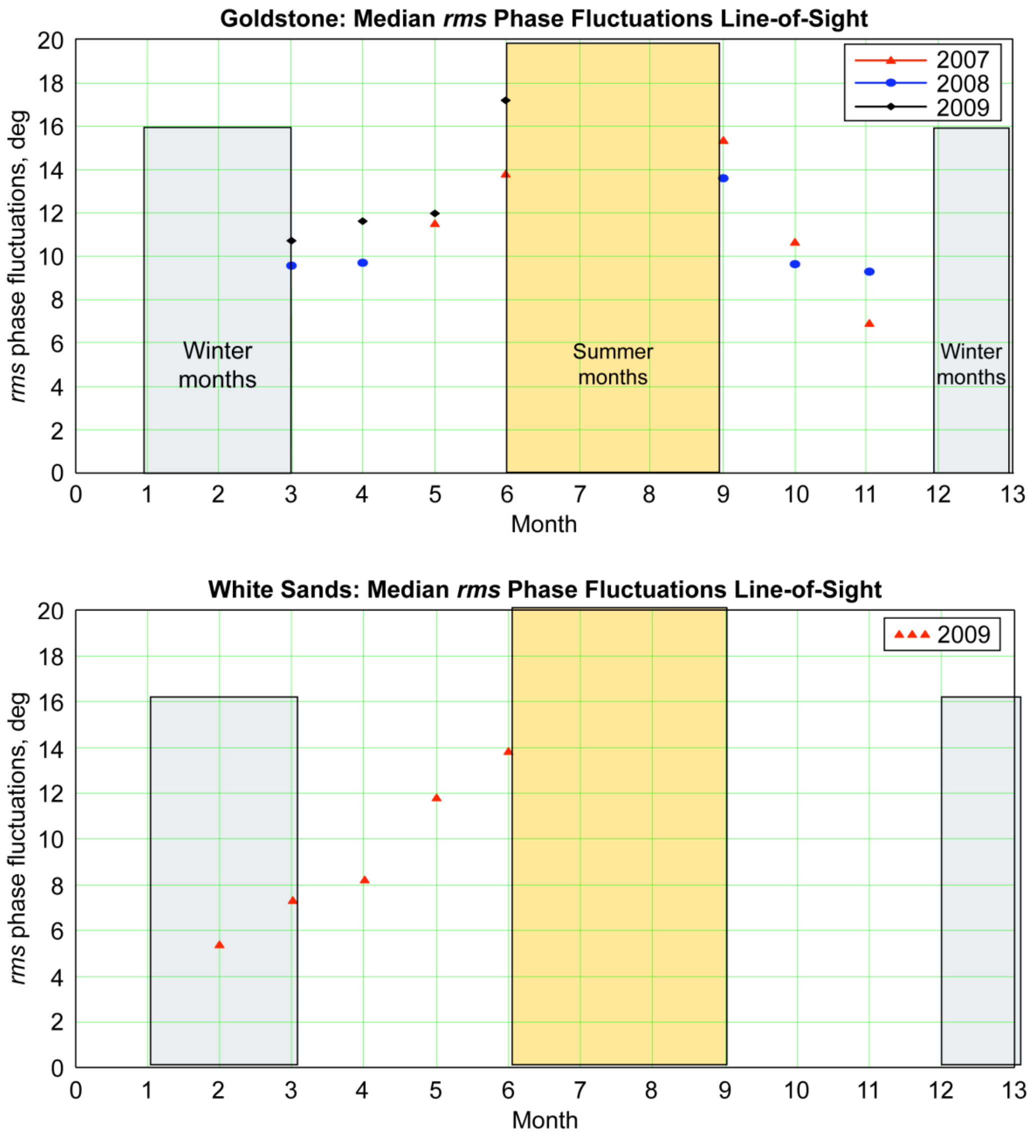

Figure 6.—Upper; The monthly median of the *rms* of the phase fluctuation over 600-s intervals for Goldstone, California. Lower; The monthly median of the *rms* of the phase fluctuations over 600-s intervals for White Sands, New Mexico.

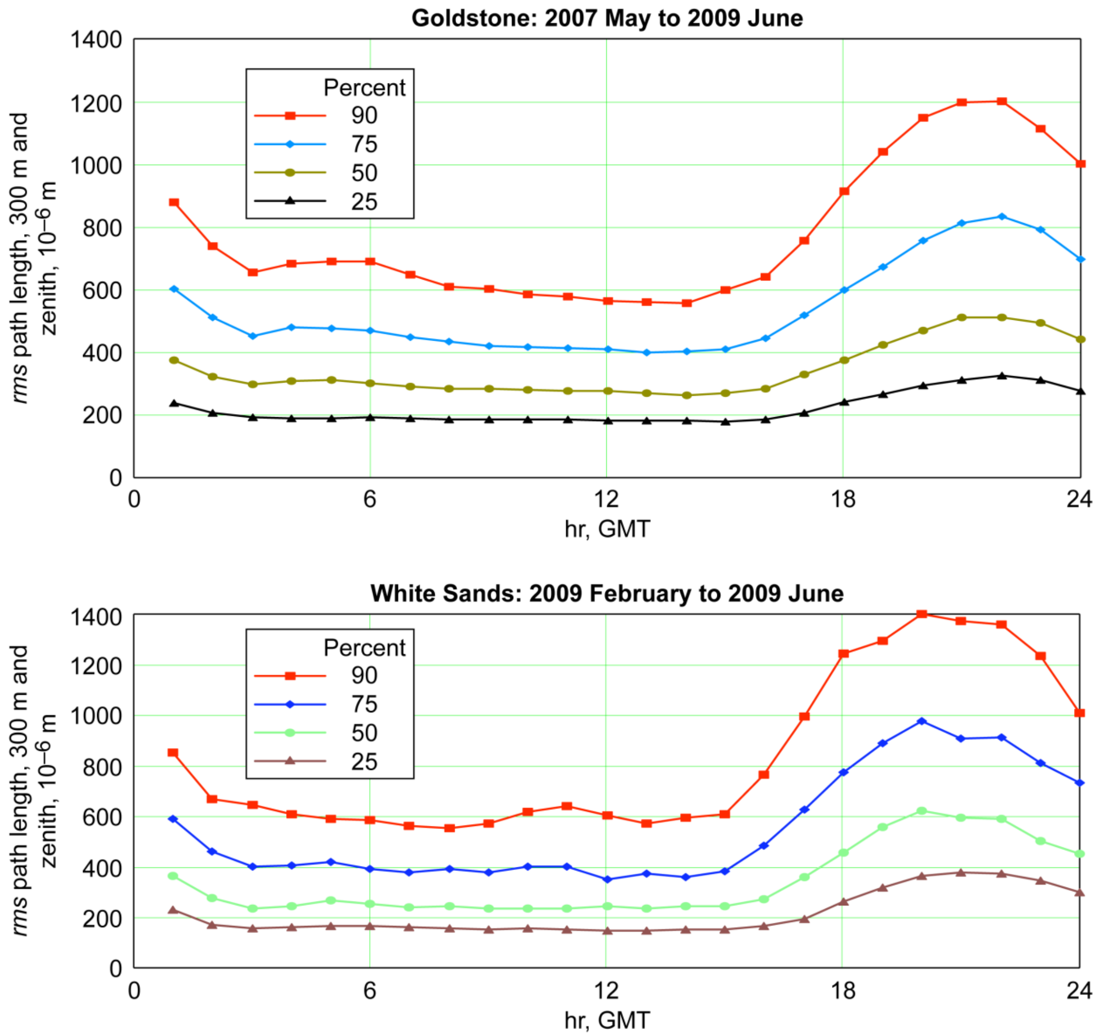

Figure 7.—Upper; Goldstone, diurnal *rms* variations of phase fluctuations converted to path length fluctuations reference to zenith and to a 300 m baseline. Lower; White Sands diurnal *rms* variations of phase fluctuations converted to path length fluctuations reference to zenith and to a 300 m baseline.

5.0 Phase Fluctuations and Ground Weather Statistics

Simultaneous measurements (February 5 to 9, 2009) of the phase fluctuations (rms), wind speed, and relative humidity for the White Sands Site is presented in Figure 8. Notice that there is a weak correlation between phase fluctuations and wind speed. This is typical to both sites.

Relative humidity appears to be the best (not a strong) indicator of the presence of water vapor molecules close to the antenna. The diurnal variation (middle portion of Fig. 8) of the wind speed observed is typical for both sites, with stronger winds in the afternoons. The relative humidity (lower portion of Fig. 8) shows some degree of diurnal variation, as well, increasing drastically on February 9, with the onset of a rain event. Further analysis must be performed to ascertain the degree of this correlation.

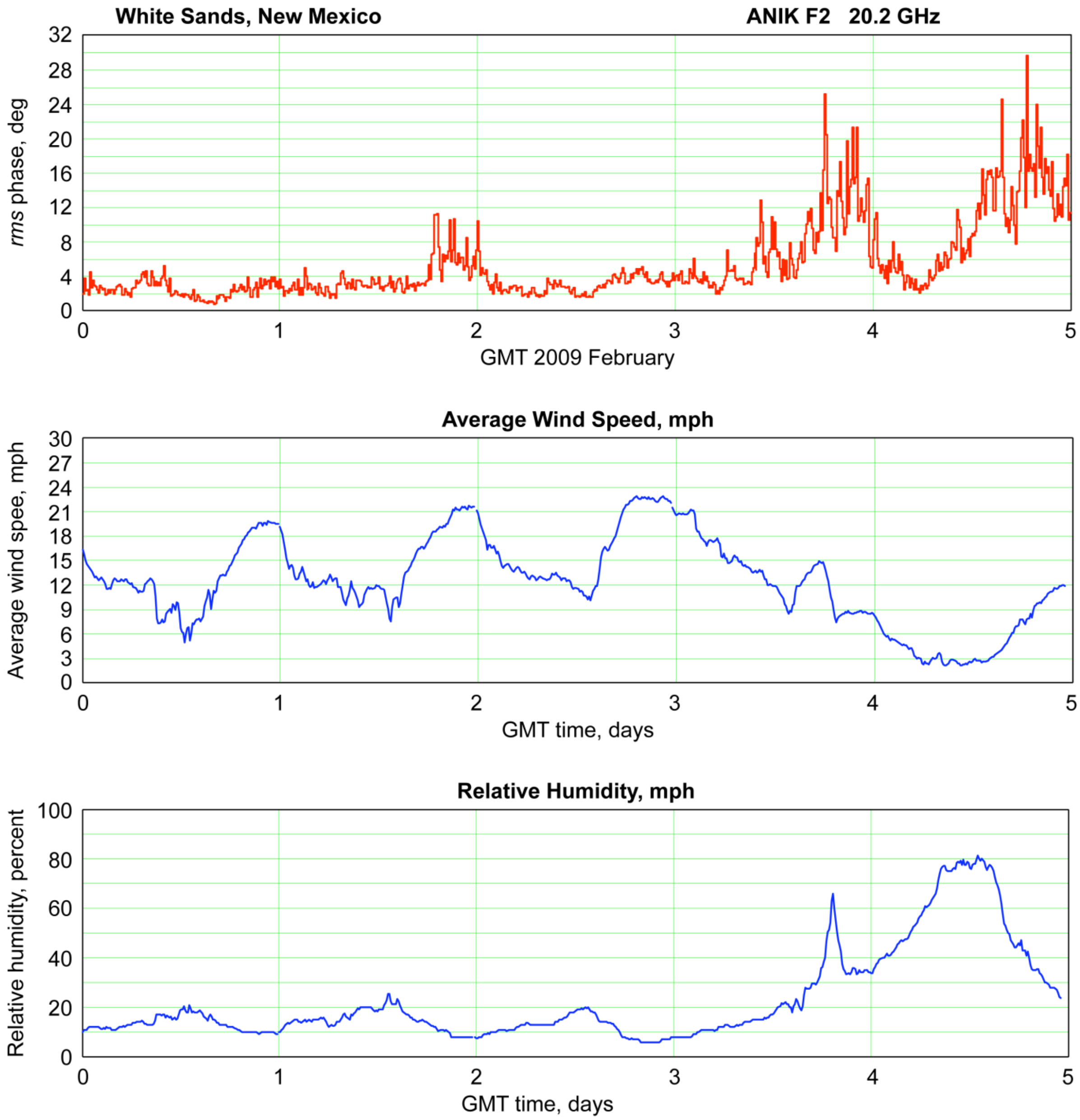

Figure 8.—Sample time series of phase fluctutation and ground weather measurements. Upper; Five consecutive days phase fluctuations; *rms* of 1-s measurements over 600-s intervals. Middle; Corresponding wind speed (mph) measurements (10 minute averages). Lower; Corresponding relative humidity, percent measurements (10 minute averages).

6.0 Conclusive Remarks and Future Work

From the results of the first 2 years of data collection in Goldstone, California, and 6 months at White Sands, New Mexico, the following conclusions can be made regarding the phase stability of the site and its potential to support a widely distributed ground-based array:

- Phase fluctuations (rms) tend to be the worst during the summer months, best during winter months, and generally worse during the day than during the evening. This phenomenon is likely due to the decreased level of atmospheric turbulence at night, and especially in the wintertime.
- Though surface meteorological measurements are not proven to be accurate predictors of weather patterns aloft, relative humidity appears to provide the best level of correlation between observed phase fluctuations and surface data. Wind speed and other surface measurements do not appear to show any significant correlation.

A statistically meaningful comparison between the two sites is not possible with the amount of data collected at White Sands. A more comprehensive comparison will be done at the end of 1 year of simultaneous data collection.

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REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-07-2010

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Path Length Fluctuations Derived From Site Testing Interferometer Data

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Acosta, Roberto, J.; Nessel, James, A.; Morse, Jacquelynne, R.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 439432.04.12.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17291

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2010-216355

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 32
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
To evaluate possible sites for NASA's proposed Ka-band antenna array, the NASA Glenn Research Center has constructed atmospheric phase monitors (APM) which directly measure the tropospheric phase stability. These instruments observe an unmodulated 20.2 GHz beacon signal broadcast from a geostationary satellite (Anik F2) and measure the phase difference between the signals received by the two antennas. Two APM's have been deployed, one at the NASA Deep Space Network (DSN) Tracking Complex in Goldstone, California, and the other at the NASA White Sands Complex, in Las Cruces, New Mexico. Two station-years of atmospheric phase fluctuation data have been collected at Goldstone since operations commenced in May 2007 and 0.5 station-years of data have been collected at White Sands since operations began February 2009. With identical instruments operating simultaneously, we can directly compare the phase stability at the two sites. Phase stability is analyzed statistically in terms of the root-mean-square (rms) of the tropospheric path length fluctuations over 10 min blocks. Correlation between surface wind speed and relative humidity with interferometer phase are discussed. For 2 years, the path length fluctuations at the DSN site in Goldstone, California, have been better than 757 μm (with reference to a 300 m baseline and to Zenith) for 90 percent of the time. For the 6 months of data collected at White Sands, New Mexico, the path length fluctuations have been better than 830 μm (with reference to a 300 m baseline and to Zenith) for 90 percent of the time. This type of data analysis, as well as many other site quality characteristics (e.g., rain attenuation, infrastructure, etc.), will be used to determine the suitability of both sites for NASA's future communication services at Ka-band using an array of antennas.

15. SUBJECT TERMS
Antenna arrays; Deep space network; Directivity; Phase noise; Atmosphere

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